Greenwood Subsurface Characterization Study
Seattle, Washington

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GREENWOOD SUBSURFACE CHARACTERIZATION STUDY
SEATTLE, WASHINGTON

1.0 INTRODUCTION

This report presents the results of our study and characterization of subsurface conditions and properties in the "Greenwood Bowl" in the Greenwood area of Seattle. The area included in this study is between about NW 85th Street and NW 97th Street and about Greenwood Avenue N and 8th Avenue NW, as shown on Figure 1. The area has shown evidence of ground settlements that have impacted facilities to varying degrees. This study was undertaken to assist Seattle Public Utilities (SPU) in evaluating potential future ground settlements that may result from maintenance and alternatives of facilities, additional development, and changes to the groundwater environment.

Our work was authorized by Nancy Ahern of SPU on June 3, 2003, in Supplemental Agreement No. 2 to Basic Agreement No. R00-38-02, between Seattle Public Utilities and Shannon & Wilson, Inc.

2.0 SCOPE OF SERVICES

Our services for this study were performed in two phases. Phase 1 involved reviewing and summarizing existing data for the area to provide a basis for Phase 2, which included subsurface explorations, soil and groundwater testing, data evaluation, and report preparation. Phase 1 was completed in 2003, the results of which were described in our report to SPU titled, "Results of Existing Document Review," dated September 24, 2003. Tasks completed for Phase 2, included:

- Performing subsurface explorations within the study area to determine the approximate aerial limits of compressible soil, the thickness of compressible soil, and the depth below ground surface (bgs) to glacial deposits.
- Performing subsurface explorations within the study area to determine (1) the depth to groundwater in upper soils and (2) if a deeper aquifer is present.
- Preparing geologic profiles, peat thickness map, and depth of compressible soil map to graphically characterize the geologic conditions.

- Performing groundwater testing and evaluation to assess (1) the influence of dewatering activities on compressible soils and (2) the potential to use groundwater recharge systems to control groundwater drawdown.
- Presenting geologic, engineering, and groundwater information by constructing a geographic information system (GIS) database.
- Preparing this report.

Our specific scope of Phase 2 field services included:

- Drilling and sampling 11 soil borings, and installing and developing monitoring wells in each boring. Drilling, soil sampling, monitoring well installation, and well development procedures are discussed in Appendix B. Boring logs and well diagrams are also provided in Appendix B.
- Conducting 22 cone penetrometer tests (CPTs). CPT field equipment, testing procedures, testing results, and probe logs are presented in Appendix C.
- Performing geotechnical laboratory tests on selected soil samples obtained during drilling. Laboratory testing included water content determinations, Atterberg Limits, grain size distributions, peat classification, and organic content. Laboratory testing methods and results are presented in Appendix D.
- Slug testing 7 monitoring wells and conducting infiltration testing in a group of 3 wells. These aquifer testing procedures, analytical methods, and results are presented in Appendix E.
- Conducting a ground penetrating radar (GPR) survey. An evaluation of the GPR survey is provided in Appendix F.

3.0 SITE DESCRIPTION

The general location of the study is shown on Figure 1, and includes the Greenwood business district and the residential area north and west of about NW 85th Street and Greenwood Avenue North, respectively. The subject area is topographically depressed and is bordered on the east by Phinney Ridge and the west by Crown Hill and Blue Ridge. To the south, the bowl is bounded by a drainage divide that separates Greenwood from the Ballard and Green Lake areas. To the northwest, the Greenwood depression drops to the headwaters of Piper's Creek, north of Holman Road. The outline of the bowl can be readily seen on a shaded relief map of the area, Figure 2.

The ground surface generally decreases about 25 feet in elevation from the southeast corner of the study area to the intersection of 8th Avenue NW and NW 97th Street. The topographic relief between the subject bowl and Phinney Ridge to the east, Crown Hill to the west, and the Ballard/Green Lake divide to the south is about 90 feet, 75 feet, and 25 feet, respectively.

In the study area, the Greenwood business district is mostly comprised of one- to two-story commercial buildings in an area of about four blocks. Several structures as high as six stories have been built in the last few years. North and northwest of the business district residential neighborhoods are comprised of mostly small, one-story houses, but scattered larger residences and multi-unit low-rise buildings exist. Streets are laid out in a rectangular grid. In many areas, the streets are at higher elevation than the ground surface and structure foundations on both sides of the street.

Settlement of roads and structures in the study area has been known for many years. Evidence of ground surface settlement includes (1) uneven road surfaces, (2) distressed and out-of-plumb buildings, (3) buildings that have been re-leveled, and (4) separation of sidewalks and roadways from buildings. We understand that there have been reports of new ground settlement in the project area in the past two years. The greatest settlement is reported near the intersection of N 87th Street with Greenwood Avenue N and Palatine Avenue N.

4.0 GEOLOGIC CONDITIONS

4.1 Geology

The geologic conditions in the study area are a legacy of the last glaciation of the central Puget Lowland between about 15,000 and 13,500 years ago and the geologic processes since then. During the last glaciation (Vashon Stade of the Fraser Glaciation) to reach the Seattle area, glaciolacustrine clay and silt, outwash sand, and lodgment till were deposited by the glacier, and were consolidated by the weight of about 3,000 feet of ice. As the ice melted and wasted, meltwater carried sand and deposited it in the area in front of the ice, and soil debris in the ice was dumped on the surface. These *recessional* deposits accumulated on top of the till.

After deglaciation, depressed areas filled in with fine-grained (silt and clay) soils that were eroded from surrounding higher ground. Lakes or ponds that developed in depressed areas were slowly filled with organic materials, turning into bogs. Fibrous peat grew and accumulated in the bogs. Where development has occurred, the peat has been covered with fill, structures, and roads or wholly or partially removed.

Based on subsurface explorations and topographic-based interpretations between the explorations, the approximate limits of the peat bog are shown on Figure 3. The limit line was drawn based on topography and the presence of peat or other organic materials in explorations. Compressible soils may exist outside of the bog limits, but they were not used to define the bog. The limits are somewhat predictable on the east, west, and south edges. Based on Subsurface Profile A-A' (Figure 5), it appears that the peat south of about NW 88th Street could have been separated from the bog area to the north. They subsequently merged into one continuous bog. To the north and northwest, we have less confidence in the limits we established because data is less plentiful and the topographic constraints are not as obvious.

Topographic maps from 1894 and 1908 that we reviewed show that Pipers Creek formerly extended southward to about NW 95th Street. The bog deposits to the south would likely have transitioned into alluvial deposits in the vicinity of NW 95th Street prior to development. The smaller organic soil area indicated on the northeast portion of the project area is probably not connected to the main organic body of the primary bowl. Although some of the explorations indicate the presence of peat, this separate organic soil area may not be a contiguous peat bog; it may be a series of small, discontinuous, organic-filled depressions.

One of the anomalous geologic features in the Greenwood bowl is a deep depression near the intersection of NW 87th Street and Palatine Avenue N, as shown by exploration GP-38. This may be a large, glacial pothole that was filled with about a 30 feet thickness of sand, silt, and clay prior to development of an organic bog.

Based on explorations in the study area, a generalized stratigraphic column (from youngest to oldest) would be as follows:

- Holocene Fill (Hf) – Loose to dense, fill materials comprised of many different soil types.
- Holocene Peat (Hp) – Very soft to soft, organic silt and fibrous peat with lenses of silt, clay, and fine sand.
- Holocene lake deposits (Hl) – Very soft to stiff clay, silt, and very loose to medium dense fine sand, with trace of organics.

- Vashon Recessional deposits (Qvro) – Loose to medium dense, silty to clean, fine and fine to medium sand, trace of gravel.
- Vashon Ablation Till (Qvat) – Medium dense, clayey, gravelly, silty sand.
- Vashon Till (Qvt) – Very dense, gravelly, silty sand.
- Vashon Till-like Diamict deposit (Qvd) – Very dense, slightly silty to silty sand with varying amounts of gravel.
- Vashon Advance Outwash (Qva) – Very dense, clean to slightly silty sand with varying amounts of gravel.
- Vashon Glaciolacustrine Deposits (Qvgl) – Hard, clayey silt and silty clay.

Geologic profiles along three alignments are presented on Figures 5 through 7. One or more of the above units may be missing at any particular location.

Two terms that are used in this report are "peat" and "compressible soil." They both encompass a group of soils, but for simplification in this report, we have chosen the succinct terms.

"Peat" herein includes organic soils that may be:

- Organic (true peat) soil with more than 75 percent organic content (according to ASTM D 2974-00 and ASTM D 4427-92 (97)).
- Organic silt with less than 75 percent organic content, but containing a significant amount of fibers in the matrix to give it organic engineering properties.

"Compressible soil" includes those inorganic soils that are very soft to stiff, fine-grained silt and clay or very loose to medium dense granular soil, which, if subjected to dewatering or loading, could settle or compress.

4.2 Groundwater

Groundwater information within the study area was compiled from the new exploration program and from available test pit, boring, and well logs. These data, including depth to groundwater, measurement date, and groundwater elevation, are summarized in Tables G-3 and G-4 (Appendix G).

Groundwater depths measured in borings, wells, and CPTs in the study area range from at or near the ground surface to approximately 20 feet below ground surface (bgs). Surface topography and the slope of the water surface control the depth to groundwater. Groundwater is generally shallowest within the topographic depression that forms the headwaters of Piper's Creek, near the northwest corner of the study area, and deepest in the slightly elevated upland areas bordering the study area to the south, west, and east.

Shallow groundwater principally occurs within fill, peat, and recessional outwash deposits under unconfined conditions. Groundwater within these deposits appears to be perched on underlying, lacustrine, till or other low permeability deposits. Explorations completed within the advance outwash deposits that underlie the till indicate groundwater under confined or artesian conditions.

The depth to groundwater in the explorations completed for this study ranged from about 2 to 10 feet bgs in the fill, peat, Holocene lacustrine, and recessional outwash soils. In the deeper advance outwash deposits, groundwater levels ranged from about 1 foot bgs to 3 feet above ground surface. Groundwater elevations range from about 280 feet along the flanks of the bowl, to about 230 feet at the northwest edge of the bowl, toward the headwaters of Piper's Creek.

Historic groundwater information (Dames & Moore, 1972) states that the groundwater table in the winter months is about 1 to 2 feet below the ground surface. The report also states that the central area of the peat deposit groundwater may fluctuate from at or above the surface during wet periods to 5 to 10 feet below the surface in the summer months. The Dames & Moore report was prepared prior to installation of the storm drain system in the study area. Ongoing groundwater level monitoring will provide additional information on groundwater level fluctuations in the Greenwood area.

The direction of shallow, unconfined groundwater flow in the study area is primarily controlled by the water table elevation, local ground surface topography, and topography of the top of till, or till-like or hard clay layers. Utilities and structures may provide preferential groundwater paths and impact local groundwater flow directions. In general, groundwater in unconfined conditions flows from areas of high elevation to low elevation. A groundwater elevation contour map based on compiled boring and well data and linear interpolation between the data points is provided on Figure 3. This map indicates that shallow groundwater predominantly flows from the east, south, and west toward the topographic basin in the central portion of the study area. From here, the predominant flow direction is toward the northwest and Piper's Creek.

The direction of deeper, confined groundwater flow is less well defined. Based on sparse available data and professional experience, groundwater within the advance outwash deposits below the till likely flows generally toward the west and the regional groundwater discharge area formed by Puget Sound, and northwest towards Piper's Creek. In addition, the deeper, confined groundwater system exhibits an upward or vertical flow component in some areas. This upward flow may contribute to groundwater in the shallow deposits. The ability for deeper groundwater to flow upward, however, is controlled or limited by the relative permeability of the confining till, till-like, or other fine-grained silt and clay deposits that overlie the advance outwash.

4.3 Hydraulic Conductivity of Greenwood Soils

Hydraulic conductivities of the soils in the Greenwood Bowl were estimated from slug tests completed in the monitoring wells installed for this study. Testing procedures and analysis of the slug tests are described in Appendix E. Initially, the focus of the hydraulic conductivity testing was on the peat deposits. However, because the peat deposits encountered at the monitoring well locations were thin, isolation of the screened portion of the wells within the peat zone was difficult. Soil deposits above and below the peat (especially the fill) influenced the test results. In places where the peat was too thin to screen or absent, other soil units were tested. The results of the slug tests indicate the peat has a hydraulic conductivity ranging from about $1x10^{-5}$ to $1x10^{-4}$ centimeters per second (cm/sec). Other soil units tested included recessional and advance outwash. Hydraulic conductivity of these units ranged from about $2x10^{-4}$ to $2x10^{-3}$ cm/sec.

4.4 Injection Testing

Injection testing was completed to evaluate the ability of the peat to be recharged as a potential mitigation measure to offset construction dewatering induced drawdown. The testing procedures and analysis are described in Appendix E. The test well is located near the intersection of 2nd Avenue NW with NW 87th Street. With a water level in the test well (TW-1) maintained at ground surface, injection of water into the peat was limited to about 0.04 gallons per minute at the end of the 12-hout test. Water levels in monitoring wells installed in the peat at a distance of 5 and 10 feet from the test well increased by 0.6 and 0.2 feet, respectively. There was a delay in the maximum water level increase achieved at each well, with MW-1 peaking approximately 2,300 minutes (more than 38 hours) after the end of the injection test and the water level peaking in MW-2 approximately 1,100 minutes (more than 18 hours) after the end of the injection test.

5.0 CHARACTERISTICS OF GEOLOGIC DEPOSITS

5.1 Fill

We encountered fill in the majority of explorations completed for this study. The fill is highly variable in consistency and density. Standard Penetration Test (SPT) blow counts and Cone Penetrometer Test (CPT) shear strength for the fill materials at the exploration locations are presented on the exploration logs in Appendix A. The fill is generally less than 5 feet thick and is comprised of a variety of soil types and debris.

5.2 Peat

Peat thickness ranges from about 0 to 5 feet around the edges of the Greenwood Bowl to about 17 feet near the intersection of NW 90th Street and 5th Avenue NW. Peat thickness is presented on Figure 7. Peat thickness observed in our explorations and observed in explorations by others is presented in Table G-1.

Organic contents of selected samples were determined by burning the samples (see Appendix D for test description). As shown on Table D-1, only two of the eight samples would be classified as true peat (greater than 75 percent organic content). The other five contained less than 75 percent organic content, so they are actually peaty organic silt. However, for purposes of this study and report, this organic-rich layer will be referred to as the "peat layer."

Two categories of peat were recognized. In borings GB-5 and GB-6, the peat was comprised of coarse, long fibers criss-crossing, fine-fibrous peat, and contained amorphous-granular peat. The coarse, long fibers were 2 to 3 mm across. In boring GB-3, the material was amorphous-granular peat containing non-woody fine fibers, with scattered, vertically aligned, long, coarse fibers. Full descriptions for each classified sample are provided in Appendix D, Table D-2.

The engineering characteristics of the peat in the Greenwood Bowl are not well known. Results for consolidation tests on peat samples were included in the geotechnical reports prepared for two projects (Appendix G, Data Sources J and A1). A field trial to preload the peat was performed for one property (Appendix G, Data Source I). The consolidation tests and preload demonstrated that the peat is highly compressible. Field observations of roadway, sidewalk, and structure settlement and damage confirm that the peat is compressible.

We did not perform consolidation or shear strength tests on the peat for this study. Peat compressibility at any location depends on depositional and plant growth environment, fiber content, and stress and groundwater history. In general, peat is subject to compression when loads applied to it are increased. Load increase on the peat could result from lowering of groundwater and change of piezometric conditions and from direct application of loads over the peat (e.g., fill or structures).

In general, peat has low shear strength and is unsuitable for building structures on except for lightweight structures that can accommodate total and differential settlement. It is sensitive to fluctuations in the water level and water content.

5.3 Hl

Holocene lacustrine (lake or pond) deposits underlie much, but not all, of the study area. They consist of very soft to very stiff silty clay with organics and very loose to medium dense, silty fine sand and fine sandy silt. Their thickest occurrence is near the intersection of Palatine Avenue NW and NW 87th Street. They are compressible, have low shear strength, and can only accommodate lightweight structures. They are sensitive to fluctuations in water level and water content.

5.4 Qvro

Vashon recessional outwash deposits are found in scattered locations throughout the basin. They consist of medium dense, brown and gray, slightly silty to silty sand. They are moderately compressible, have moderate shear strength, and can accommodate lightweight and moderately heavy structures.

5.5 Qvat

Vashon ablation till is found in scattered and limited spots in the basin. It consists of medium dense, clayey, gravelly, silty sand. It has characteristics similar to recessional outwash, except it normally has a lower permeability due to the clay particles in its matrix.

5.6 Qvt

Vashon till is found underlying the highly and moderately compressible soils throughout most of the basin. The till has high shear strength, will compress little when loaded, and can support high structure loads. It has low permeability. Groundwater commonly perches on top of this layer.

5.7 Qvd

Vashon till-like diamict is intermediate between till and outwash in grain-size characteristics. It is very dense, slightly silty to silty sand with a wide range of gravel content. It is said to be "semi-permeable," because it has a permeability intermediate between low permeability till and high permeability outwash. It will compress little when loaded, has high shear strength, and can accommodate high structure loads.

5.8 Qva

Vashon outwash is found underlying till in the normal Vashon stratigraphic sequence. It is a very dense, clean to slightly silty, gravelly sand or sandy gravel. It will compress little when loaded, has high shear strength, and can accommodate high structure loads. It has high permeability.

5.9 Qvgl

The Vashon glaciolacustrine deposit (Lawton clay) locally underlies younger Vashon deposits. It is hard, clayey silt and silty clay. It will compress some, but not significantly, when loaded; has moderately high shear strength; and can accommodate moderate structure loads. It has a low permeability, except along horizontal sand lenses or vertical joints.

6.0 DISCUSSION

6.1 Compression of Peat and Other Soft/Loose Soils

Compression and subsequent settlement of peat and other compressible soils occur primarily as a result of lowering of groundwater levels and loading of these soils.

Numerous factors could contribute to groundwater lowering, including:

- Long-term drought cycles.
- Seasonal fluctuations in groundwater and precipitation.
- Groundwater inflow into and drainage by subsurface pipes and their trench backfill.

- Groundwater withdrawals by foundation sumps, foundation drains, and construction dewatering activities.
- Reduced groundwater recharge rates associated with the paving of streets and parking lots, diversion of roof drainage and surface runoff to the storm drain system, or other site development activities that limit stormwater infiltration.

Loading of compressible soil in the study area has occurred as a result of fill placement for construction of roadway, sidewalk, and surface parking facilities; construction of structures with shallow foundation systems, such as residences; and utility and excavation backfill and site grading. For larger structures, foundation elements would likely extend down into more competent soils, and loading of compressible soils as a result of these structures would be limited or not occur.

6.2 Groundwater Lowering Induced Settlement

In the study area, primary settlement of peat and compressible soils resulting from groundwater lowering is likely nearly complete within the vertical zone where groundwater levels seasonally cycle to lower elevations due to natural fluctuation or where they have been artificially lowered, and where these conditions have occurred for many years. Additional groundwater drawdown could contribute to additional settlement of underlying soils.

Some structures within the project area may have basements or other below-grade levels. Continuous pumping to remove water from around or within below-grade portions of structures could lower groundwater levels and contribute to settlement.

Settlement caused by groundwater lowering may be delayed, occurring weeks or months after groundwater lowering. Likewise, settlement-caused impacts on structures, utilities, roadways, and other improvements may not be observed or become problematic until sometime after groundwater lowering. Because of the delayed response to groundwater lowering, by the time settlement or damage is observed, it is generally too late to stop settlement and avoid damage to improvements by stopping groundwater removal. Settlement-caused damage cannot be repaired by restoring or raising the groundwater elevation because the peat and other compressible soils at the site will not expand to their original thickness after they have been compressed.

6.3 Construction Dewatering

For structures completed below groundwater, temporary construction dewatering has been used to prevent groundwater from entering the excavation until the subsurface portion of the structure is completed. Temporary construction dewatering techniques may have included the use of sumps and ditches within the excavation, and/or dewatering wells or vacuum-extraction well points outside the excavation. Lowering of groundwater by these dewatering systems may have increased the effective stress acting on compressible soils leading to ground settlements. In general, the use of these systems would be short-term. The area of influence of these dewatering systems on groundwater levels depends on the engineering properties of the soils being dewatered, the type of system used, the length of time of dewatering, and other factors.

6.4 Structure Drainage Systems

We did not conduct a survey of, nor were we provided information regarding, foundation drainage systems for structures within the study area. Where drain pipes, sumps, or other drainage systems are present they may contribute to groundwater lowering. Dewatering system operation could affect groundwater conditions many tens or hundreds of feet from the site at which the system is located. The area of influence of these dewatering systems on groundwater levels depends on the engineering properties of the soils being dewatered, the type of system used, the length of time of dewatering, and other factors. Long-term operation increases the magnitude of groundwater lowering and the size of the area affected. As discussed above, groundwater lowering could contribute to settlement of compressible soils.

6.5 Structure Foundation Systems

Based on our observations, a number of older buildings and residential structures in the project area are likely founded on shallow spread footings. Many of these structures are likely founded on ground underlain by compressible soils, including peat and Holocene clay. A number of structures show signs of past settlement, re-leveling, wracking/leaning, cracked footings and foundation walls, and repairs. Where structures have basements, some or all of the compressible soil below the structures may have been removed. We observed undulating and damaged slab-on-grade floor slabs in some structures located on the east side of Greenwood Avenue North between N 85th Street and N 87th Street. Based on discussions with residents at the November 18, 2003, Greenwood community meeting, at least two residences near the intersection of Palatine Avenue N and N 87th Street were underpinned within the past couple of years using helical anchors and 2-inch-diameter pipe piles.

There appears to be a general consensus among engineers who prepared the geotechnical reports we reviewed for this study that the peat is highly compressible and unsuitable for building structures over. Table 1 presents alternative methods for dealing with potential settlement of structures constructed on ground underlain by peat that are recommended in those geotechnical reports. Some reports provide recommendations for multiple alternative foundation systems.

Within the project area and where structures are underlain by peat or other compressible soil(s) and excess settlement could occur, the alternative foundation systems listed below might also be considered to support structures.

- Intermediate depth stone columns, e.g., Geopier™ foundations
- Micropiles

TABLE 1
STRUCTURE FOUNDATION SYSTEMS IN ENGINEERING REPORTS

Method	Data Source
Do nothing, shallow footings – total and differential settlement acceptable.	W (basement excavation would reduce load and tendency to settle), J (avoid area underlain by peat), AI (avoid area underlain by peat)
Excavate peat and found footings below peat (includes constructing a basement) or replace excavated peat with structural fill / CDF.	T, X, K, Q, N, AI
Use lightweight fill to reduce settlements below fill.	E
Surcharge/preload the peat below fills and structures.	I (recommendation revised after excessive peat settlement occurred during test preload), Q
Driven steel pipe piles (> 6 inches) or small-diameter pipe pile (≤ 4") foundations, with grade beams.	I, N, and personal communication with two study area residents on 11/18/03
Timber piles	A, K, N
Augercast piles or drilled pier foundations, with grade beams.	E, M, X, W, U, K, AH, Q, N
Helical piers	Personal communication with a study area resident on 11/18/03

Notes:
* Only geotechnical reports (data sources) that provided recommendations for structures founded in areas underlain by peat are included in the above table.

Selection of which foundation alternative to pursue, whether one of those listed in Table 1, or those listed above, depends on peat thickness, groundwater conditions, depth to bearing layer, time constraints, project economics, structure loads, and other factors. We recommend that foundation and construction alternatives be evaluated for each project.

Recommendations for construction of ventilated crawl spaces are provided in Data Source M (Appendix G) to reduce potential buildup of methane gas. Providing means to avoid methane gas buildup may be appropriate for some structures; however, we did not evaluate this potential need for this study.

6.6 Backfill Adjacent to Structures

Sloped excavations may have been made around the perimeter of work areas to facilitate construction of existing below-grade structures. If structural fill was used to backfill these excavations or fill was placed below sidewalks and driving surfaces, and if the placed fill overlies peat or other compressible soil, then settlement of the underlying soil may occur. Placement of fill over peat and other compressible soil may be partially responsible for observed settlement adjacent to older structures along the east side of Greenwood Avenue N between N 85th Street and N 87th Street (Appendix G, Data Source AF), and for settlement in sidewalks and pavements observed adjacent to the new buildings at the southwest and northwest corners of the intersection of Greenwood Avenue N and N 87th Street.

6.7 Roadways and Utilities

We observed settlement of roadways, pavement edges, and sidewalks. We also observed that roadways in the study area are often crowned and higher than the ground surface on either side of them. Mr. Herb Allwine, City of Seattle Department of Transportation, provided tabulated and summarized maintenance information for the study area. This information shows that settlement has been documented in the project area since 1958. Maintenance records report repair of sinkholes; broken sidewalks, pavement, and utilities; bumps and dips in pavement; and observation of voids below sidewalks and adjacent structures. Twenty of the 25 records provided to us are for occurrences since 1998. Fifteen of these are for locations within the 8500 to 8700 blocks between Greenwood Avenue N and 3rd Avenue N.

We did not review data that documented the construction methods for roadways, utilities, and sidewalks. However, based on our observations, it is likely that the roadways were constructed principally by placing fill material over the native deposits. Additional fill material and pavement overlays were likely added as settlement occurred. It is likely that over the years settlement of peat and soft compressible soils below the centerline of roadways has occurred and the rate of settlement has slowed. Settlement of peat below sidewalks and along roadway edges appears to still be occurring in some areas, e.g., along Greenwood Avenue N and Palatine Avenue N between N 85th Street and N 87th Street.

Recommendations for storm drain installation to limit settlements are presented in Dames & Moore, 1972; and Wilsey & Ham, 1972. Where utilities were installed in or over peat deposits and where these utilities were backfilled with granular fill, settlement of the utility would be expected to have occurred. Where these utilities have been in place for many years, there is a reduced potential for future settlement.

6.8 Construction Recommendations

Project-specific construction and foundation recommendations should be developed for each project in the Greenwood Bowl. General construction recommendations are presented in Appendix A.

7.0 CONCLUSIONS

7.1 Groundwater

Groundwater conditions in the Greenwood area consist of a shallow unconfined aquifer in the fill, peat, lacustrine, and recessional outwash deposits, and a confined aquifer in the deeper advance outwash deposits. Groundwater is encountered near ground surface to about 20 feet bgs in the higher topographic areas. The direction of groundwater flow in the shallow aquifer is towards the topographically low center of the Greenwood Bowl, then northwest toward the headwaters of Piper's Creek. In the deeper confined aquifer, the direction of groundwater flow has not been confirmed, however it is likely to the west and to the northwest toward Piper's Creek. Upward flows from the confined aquifer, through the till and till-like soils to the shallow aquifer, are also expected to occur and contribute to shallow aquifer recharge.

Groundwater levels in the shallow aquifer appear to have been decreasing over the years. Historically, the Greenwood bowl area was known to be a wet, swampy farmland area. Anecdotal evidence indicates that prior to the installation of an extensive storm drain system in the 1970s, elevated groundwater during the wet season caused local flooding. Other indirect evidence of declining groundwater levels includes ground settlement throughout the Greenwood area. Lowering of groundwater levels in the shallow aquifer results in a reduction of the effective stress in shallow soils, and with the presence of compressible soils, such as peat, ground settlement is the result.

Groundwater levels have declined in the shallow aquifer as a result of several factors, including:

- Reduction in recharge as a result of construction of impervious surfaces.
- Reduction in recharge as a result of diversion of surface and roof runoff to storm drain systems.
- Changes in drainage patterns as a result of local grading of the ground surface.
- Installation of the 1970s storm drain system.
- Natural groundwater fluctuations, including seasonal changes.
- Climatic change.
- Construction dewatering.
- Permanent drainage systems in subsurface structures.

In order to reduce the decline of groundwater levels in the shallow aquifer, recharge of the shallow aquifer to offset the above impacts is recommended. Continued groundwater monitoring is recommended to evaluate the impacts of seasonal fluctuations and climatic change on groundwater levels, and to provide a baseline for identifying additional declines in the shallow groundwater levels. Lowering of the shallow aquifer may also impact the deeper aquifer because of increased upward flow that would result.

7.2 Peat and Compressible Soils

Peat and compressible soils underlie portions of the study area, see Figures 3 through 8. These soils are subject to compression when groundwater elevations and piezometric pressures are lowered and when loaded. Observed and reported settlement likely resulted from a combination of these factors. Recent accelerated settlement in areas where loads have not been increased are likely the result of groundwater removal, e.g., along Palatine Avenue N near NW 87th Street and near the intersection of NW 87th Street and Greenwood Avenue N. Continued groundwater removal and removal of groundwater from other locations within the study area could contribute to additional or new settlement, and should be avoided where settlement could impact structures, utilities, roadways, and other improvements.

8.0 CLOSURE

8.1 Recommendations for Additional Monitoring/Studies

Although the studies completed for this report shed more light on the groundwater and compressible soil conditions in the Greenwood Bowl, there are unknowns that can only be understood by performing continuing, long-term monitoring and evaluating the data. Those additional monitoring/studies include:

- Long-term monitoring of piezometers using pressure transducers and data recorders.
- Installing additional storm sewer monitoring points.
- Installing ground surface monitoring points throughout the study area and recording elevations annually.
- Evaluating long-term data after five years and preparing a basin water budget.

8.2 Limitations

All interpretations of the geologic conditions are general in nature. Borings, test pits, and CPTs should be used only at their specific locations. Conditions between them may vary from that shown in the figures in this report. Static groundwater information is presented based on single or a few readings. Groundwater levels may vary from these in the future. The source of inflow of water from the surrounding area and the effects of dewatering by pumping or passive subdrainage are known in general but not specifically for any particular structure or source.

The conclusions reached in the report are based on site conditions and information as they existed at the time of the study. This work was done in accordance with generally accepted engineering and geologic practice in this area at this time. No other warranty is made, either express or implied.

We have prepared the document, "Important Information About Your Geotechnical Report" (Appendix J) to assist you and others in understanding the use and limitations of our reports and to serve as an explanation of the assumptions under which this report was prepared.

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Hydrogeologic items related to hydrogeology, hydrogeologic setting, hydrostratigraphy, and groundwater control were prepared by or prepared under the direct supervision of Richard J. Martin, L.H.G.

Geotechnical items related to geology, geologic unit designations and descriptions, and ground characterization were prepared by or prepared under the direct supervision of William T. Laprade, L.E.G.

Geotechnical items related to soil engineering properties, foundation types, and geotechnical construction considerations were prepared by or prepared under the direct supervision of Stanley R. Boyle, P.E.

9.0 REFERENCES

Dames & Moore, 1972, Report of soils investigation and environmental impact studies, proposed storm drain improvement, North Greenwood West portion of south Carkeek Park drainage system: Report by Dames & Moore, Seattle, Wash., for the City of Seattle, Wash., March 24, rev. March 30, 34 pp.

Wilsey & Ham, Inc., 1972, Final environmental statement for North Greenwood West storm drains: Report by Wilsey & Ham, Inc., Seattle, Wash., for the City of Seattle, Seattle, Wash., February, 6 pp. [excerpts] *in* City of Seattle, Final Environmental Statement for North Greenwood West storm drains, North Greenwood West neighborhood & Piper Creek Canyon: Report by City of Seattle, Seattle, Wash., May, 1972.